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*Operation*

**SUN BEAM**

**SHOT SMALL BOY**

PROJECT OFFICERS REPORT—PROJECT 1.7

SHOCK SPECTRUM MEASUREMENTS (U)

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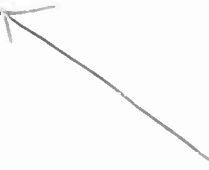


## ABSTRACT

A total of 16 reed gages of a design which had previously been used in Operations Plumbob, Hardtack, Hardtack II, and Nougat were installed in the Small Boy Event. These gages recorded horizontal and vertical displacement shock spectra at four stations between 185 feet and 290 feet of ground zero. Some gages were placed at the surface and others at 10-foot depth. All gages yielded readable records and data is presented in both tabulated and chart form.

The gages 10 feet below the surface showed a marked attenuation at high frequencies but very little attenuation of horizontal shock at frequencies below 50 <sup>cps</sup> ~~cycles per~~ second and of vertical shock at frequencies below 25 <sup>cps</sup> ~~cycles per~~ second. A peak was noted in horizontal acceleration between 90 and 150 <sup>cps</sup> ~~cycles per~~ second at the surface and between 50 and 90 cycles at 10-foot depth. No similar peaks were noted in the vertical acceleration.

Examination of the data presented indicated that no simple scaling was possible for the ground shock which occurred. This data will have to be studied with other shock spectra data so that it may be properly weighed, and quantitative scaling rules derived.



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## SHOCK SPECTRUM MEASUREMENTS

### INTRODUCTION

Objective. The objective of this project was to measure the displacement spectrum of the ground motion at ranges of 185, 200, 245, and 290 feet from ground zero, both at the surface and at a depth of 10 feet. The displacement spectrum is a plot of peak displacement versus frequency of a set of several linear fixed-frequency oscillators (of single-degree-of-freedom) resulting from the motion of the ground.

Background. The use of self-contained mechanical reed gages, capable of measuring the displacement shock spectrum in any one direction, provided an indication of the characteristics of blast-induced and ground-transmitted ground shock under conditions of low yield loading during Operation Plumbbob (Reference 1). Additional measurements, free field and in structures, were made for high and low yield loadings during Operation Hardtack at the Pacific Proving Grounds (Reference 2). Surface measurements of the shock spectrum generated by underground nuclear detonations were made during Operation Hardtack, Phase II, and Operation Nougat (Reference 3) at the Nevada Test Site.

Measurements of the surface ground-shock spectrum were obtained during the 20-ton trial at the Suffield Experimental Station (SES),

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Ralston, Alberta, Canada, and both the surface and near-surface spectrum resulting from the 100-ton trial at SES in 1961 (Reference 4).

These data have been utilized in preparing the environmental information considered essential for the design of missile systems hard bases for the Air Force Ballistic Systems Division (AFBSD) and in theoretical studies of scaling effects.

Theory. Briefly, if a shock due to ground motions is applied to a linear structure attached to the ground, the displacement of any point of the structure relative to the ground can be expressed as a sum of principal mode responses:

$$u(t,x,y,z) = \sum q(t) \phi(x,y,z) \quad (1)$$

where:  $u(t,x,y,z)$  = displacement relative to ground  
 $q(t)$  = generalized coordinate  
 $\phi(x,y,z)$  = mode shape

An upper bound of response is obtained assuming all modes have reached their peak values at the same time.

$$u_{\max} = \sum |q_{\max} \phi| \quad (2)$$

For an acceleration input it can be shown that for each mode:

$$\ddot{q} + 2\epsilon\omega\dot{q} + \omega^2 q = -\gamma a(t) \quad (3)$$

where:  $q$  = generalized displacement relative to ground  
 $\omega$  = frequency of mode

$\epsilon$  = ratio of damping to critical viscous damping

$\gamma$  = kinematic factor =  $\int \rho \phi dv / \int \rho \phi^2 dv$

$\rho$  = mass per unit volume

$a(t)$  = acceleration of ground as function of time

The solution to Equation 3 for small damping is

$$q_{\max}(\omega, \epsilon) = \max_{t>0} \left| \frac{1}{\omega} \int_0^t a(\tau) e^{-\epsilon \omega(t-\tau)} \sin \omega(t-\tau) d\tau \right| \quad (4)$$

Assuming an idealized single-degree-of-freedom system, such as a point mass on a weightless cantilever spring, the equation of motion for the mass is

$$\ddot{Q} + 2\epsilon \omega \dot{Q} + \omega^2 Q = -a(t) \quad (5)$$

The reed shock gages, with an appropriate gage factor to adjust for stylus position and for the fact that the sets of cantilevered mass systems have distributed mass, read directly the peak displacements as solutions of Equation 5. The frequency spectrum of the peak displacements of the masses relative to the base that is being accelerated is called the displacement shock spectrum, which is defined as

$$D(\omega) = Q_{\max} = \max_{t>0} \left| \frac{1}{\omega} \int_0^t a(\tau) e^{-\epsilon \omega(t-\tau)} \sin \omega(t-\tau) d\tau \right| \quad (6)$$

If the displacement spectrum  $D(\omega)$  is known, the modal response of any other structure having the same damping as the gage is given by

$$q_{\max} = \gamma D \quad (7)$$

or the upper bound of response by (from Equation 2)

$$u_{\max} \leq \sum |\gamma D \phi| \quad (8)$$

The velocity shock spectrum is defined as:

$$V = \omega D \quad (9)$$

This quantity has the dimensions of velocity, but is not the peak velocity of the mass relative to the base. The velocity shock spectrum is useful, however, in the determination of an upper bound of strain energy in the structures.

The acceleration shock spectrum is defined as

$$A = \omega^2 D \quad (10)$$

and can be shown to be the peak absolute acceleration of the mass for small damping, namely

$$A = \max \left| \ddot{Q} + a \right| \quad (11)$$

#### PROCEDURE.

Operations. Project activities at the site consisted of placement of canisters, installation, and adjustment of gages and record plates, and subsequent postshot recovery.

Instrumentation. Gages used in this test were the Space Technology Laboratories' designed reed gages used to measure shock spectra in previous nuclear tests. The gages consisted of ten masses on cantilever springs or reeds, mounted on a rigid base. The masses and spring constants of the ten reeds were so designed that their natural frequencies covered the range between 3 and 300 cps. Nominal frequencies are 3, 10, 20, 40, 80, 120, 160, 200, 250, and 300 cps.

The masses, which move in one plane, have scribes in contact

with a polished metal record plate. A thin layer of lampblack is deposited on the record plate prior to final installation by smoking it with a candle. As the reeds vibrate after being subjected to a shock, the maximum displacement of each mass is recorded on the smoked plate by the scribes. These displacements are measured, and equivalent values for the mass motion are plotted against the natural frequencies of the reeds to obtain the shock spectrum curves for the various installations.

Sixteen gages were installed for the event, as shown in Table 1. Terminology adopted in Table 1 will be used consistently in this report. Horizontal and vertical refers to gages whose bases are horizontal and vertical, respectively, and measure response in the vertical plane containing the burst point. Tangential refers to a gage whose base is horizontal and measures response at right angles to this plane. Each gage was housed in a protective canister. Several sandbags were placed on the lid of each canister, buried flush with the earth's surface. Each 10-foot deep hole containing gages and canisters was backfilled prior to the event.

(Since accelerations expected at the close-in stations might damage reeds in the low-frequency range, a few of the 3- and 10-cycle reeds were removed prior to gage installation.) These reeds are indicated in Table 2. Figure 1 shows a typical horizontal gage installation and Figure 2 a typical vertical gage.

## RESULTS

All of the gages placed in the Small Boy Event yielded records. The maximum response of each reed corrected for scriber

location is given in Table 2. A few of the readings were questioned due to the fact that a scribe bent or skipped on the plate. With the exception of these readings, it is believed that the recorded values were within 20 percent of the true spectra values. For small displacements, the recorded values were accurate to within 0.002 inch.

The shock spectra for these gages are shown in Figures 3 through 9.

#### DISCUSSION

Two tangential reed gages were included in the Small Boy Event, since in some instances tangential gages in past events have shown responses as large or larger than horizontal gages at the same location. These gages (see Figures 5 and 7) yielded shock spectra somewhat lower than the horizontal gages at the same location. The shocks, however, were not small and were probably caused by a combination of two effects: (1) asymmetries in the expanding shock wave, and (2) reflections of shock from earth strata, faults or discontinuities.

The results are replotted in Figures 10 through 15 to show the effect of burial depth. As was expected, the attenuation at high frequencies was extremely marked, while 10 feet of cover demonstrated very little attenuation of horizontal shock at frequencies below 50 cycles per second and of vertical shock at frequencies below 25 cycles per second.

Data is replotted in Figures 16 through 19 to show the effect of range on accelerations at various frequencies. Figures 17 and 19 show a peak to be occurring in the horizontal acceleration between 90 and 150 cycles per second at the surface and between 50 and 90 cycles at a 10 foot depth. No similar peaks are noted in the vertical acceleration, Figures 16 and 18.

Examination of Figures 16 through 19 indicates that no simple scaling is possible for the ground shock which occurred. The data will have to be studied in the light of other shock spectra data in order that it may be properly weighed and quantitative scaling rules derived.

#### CONCLUSIONS

On the basis of results obtained on Project 1.7 of the Small Boy Event, the following conclusions can be drawn:

1. The objective of Project 1.7 was attained. All gages yielded valid readings, which resulted in the shock spectra of Figures 3 through 9.
2. Attenuation of air-induced ground shock with depth in soil was as expected. Large attenuations were experienced at high frequencies and little or none at very low frequencies at a 10-foot depth.
3. Transverse shocks of considerable magnitude (although less than horizontal) can occur in air-induced ground shock. These shocks were probably due to asymmetries



in the blast wave and more importantly, discontinuities in the soil.

4. Scaling laws for ground shock cannot be quantitatively deduced on the basis of the small amount of data obtained in this event. The data should be studied in the light of data from other tests in order to arrive at proper scaling relations.

TABLE 1 - LOCATION OF REED GAGES

<u>Range from Ground Zero</u>	<u>Gage Position</u>	<u>Depth</u>
135 feet	Vertical	10 feet
	Horizontal	10 feet
200 feet	Vertical	Flush with surface
	Horizontal	Flush with surface
	Tangential	Flush with surface
	Vertical	10 feet
245 feet	Horizontal	10 feet
	Vertical	Flush with surface
	Horizontal	Flush with surface
	Tangential	Flush with surface
	Vertical	10 feet
290 feet	Horizontal	10 feet
	Vertical	Flush with surface
	Horizontal	Flush with surface
	Vertical	10 feet
	Horizontal	10 feet

TABLE 2  
FREQUENCY, DISPLACEMENT DATA

Station 507.01, 185 Feet From SZ			
Vertical 10 Foot Depth, Gage No. 17		Horizontal 10 Foot Depth, Gage No. 1	
F(cps)	D(inches)	F(cps)	D(inches)
3	Removed	3	Removed
10	Removed	10	Removed
23	1.23 <sup>(1)</sup>	23	0.234
51	0.310	48	0.067
88	0.074	90	0.047
138	0.043	138	0.013
181	0.020	177	0.007
220	0.005	215	0.005
260	-----	262	-----
286	0.007	288	-----

Station 507.02, 200 Feet From SZ									
Vertical 10 Ft. Depth Gage No. 7		Horizontal 10 Ft. Depth Gage No. 20		Vertical Surface Gage No. 8		Horizontal Surface Gage No. 21		Tangential Surface Gage No. 5	
F(cps)	D(inches)	F(cps)	D(inches)	F(cps)	D(inches)	F(cps)	D(inches)	F(cps)	D(inches)
3	Removed	3	Removed	3	Removed	3	Removed	3	Removed
9.5	1.36	10.1	0.762	10	Removed	10	Removed	10	Removed
23	1.08 <sup>(1)</sup>	23	0.173	23	0.927 <sup>(1)</sup>	23	0.242 <sup>(3)</sup>	24	0.214 <sup>(2)</sup>
48	0.384	49	0.112	49	0.690 <sup>(2)</sup>	49	0.22 <sup>(3)</sup>	50	0.134
90	0.094	90	0.029	91	0.543 <sup>(1)</sup>	90	0.450	90	0.133
138	0.132	138	0.008	137	0.354	136	0.043	138	0.034
182	-----	181	-----	178	0.267	182	0.020	180	0.007
216	-----	221	-----	221	0.137	220	0.017	221	0.009
262	-----	254	-----	254	0.116	256	0.014	262	0.005
281	-----	283	-----	288	0.098	288	0.020	288	0.003

- (1) At end of recording range  
(2) Scriber skipped  
(3) Scriber failed  
(4) Hit by another reed  
(5) No record obtained

TABLE 2 (continued)  
FREQUENCY, DISPLACEMENT DATA

Station 507.03, 246 Feet From SZ									
Vertical 10 Ft. Depth Gage No. 4		Horizontal 10 Ft. Depth Gage No. 16		Vertical Surface Gage No. 12		Horizontal Surface Gage No. 26		Tangential Surface Gage No. 25	
F(cps)	D(inches)	F(cps)	D(inches)	F(cps)	D(inches)	F(cps)	D(inches)	F(cps)	D(inches)
2.6	3.02	2.5	2.76	2.6	4.46	2.97	2.78	3.0	0.362
9.9	1.42	9.8	0.310	10.5	1.56 <sup>(1)</sup>	10.3	0.888	10.0	0.109
23	0.838	23	0.243	23	0.713	22	0.256	22	0.083
51	0.086	50	0.193	48	0.551	47	--- <sup>(5)</sup>	48	0.053
91	0.031	88	0.035	90	0.278	91	0.121	88	0.066
138	0.009	138	0.009	137	0.328 <sup>(4)</sup>	139	0.124	141	---- <sup>(3)</sup>
181	0.007	180	0.005	180	0.181	179	0.029	186	0.011
221	-----	222	0.004	215	0.210 <sup>(2)</sup>	224	---- <sup>(5)</sup>	226	0.011
262	-----	261	-----	262	0.051	276	0.032	270	0.024
288	-----	286	-----	289	0.108	298	0.030	300	0.024

Station 507.04, 290 Feet From SZ							
Vertical 10 Ft. Depth Gage No. 14		Horizontal 10 Ft. Depth Gage No. 15		Vertical Surface Gage No. 32		Horizontal Surface Gage No. 2	
F(cps)	D(inches)	F(cps)	D(inches)	F(cps)	D(inches)	F(cps)	D(inches)
3.1	2.09	2.5	2.04	3.1	4.14 <sup>(1)</sup>	3.3	1.83
9.4	1.36	10.3	0.114	10.8	.... <sup>(5)</sup>	10.6	0.258
23	0.52	22	0.160	24	1.02 <sup>(1)</sup>	23	0.116
49	0.091	49	0.075	49	0.698	49	0.123
88	0.020	90	0.018	91	0.262	88	0.094
137	0.009	136	0.004	137	0.218	138	0.043
181	-----	178	-----	183	0.116	180	0.020
214	0.004	218	-----	222	0.094	213	-----
250	-----	258	-----	272	0.095	258	0.007
288	-----	287	-----	288	0.088	289	-----

- (1) At end of recording range  
(2) Scriber skipped  
(3) Scriber failed  
(4) Hit by another reed  
(5) No record obtained

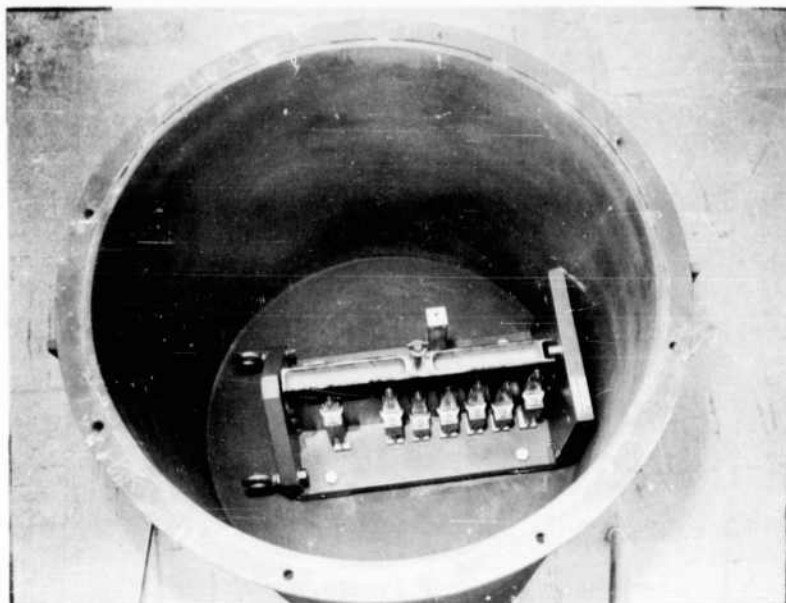


Figure 1 Typical installation of a horizontal reed gage in a protective canister. (STL 71869-61)

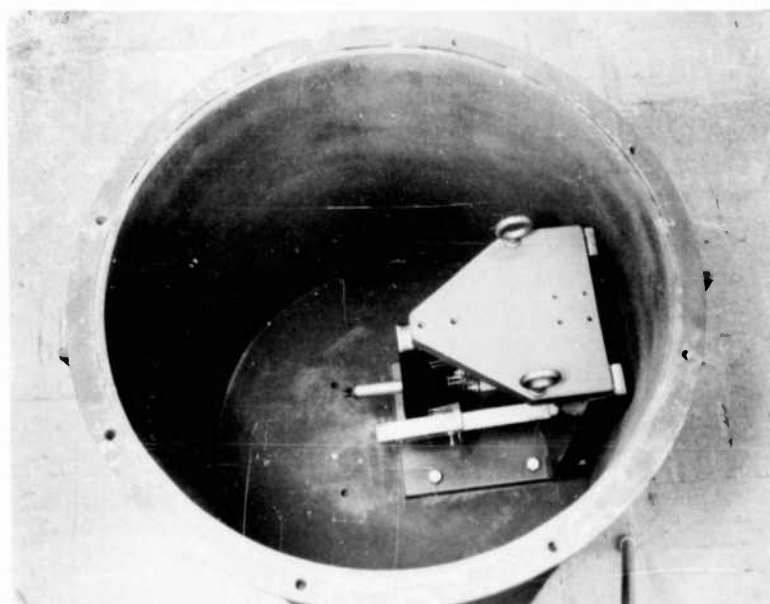


Figure 2 Typical installation of a vertical reed gage in a protective canister. (STL 71870-61)

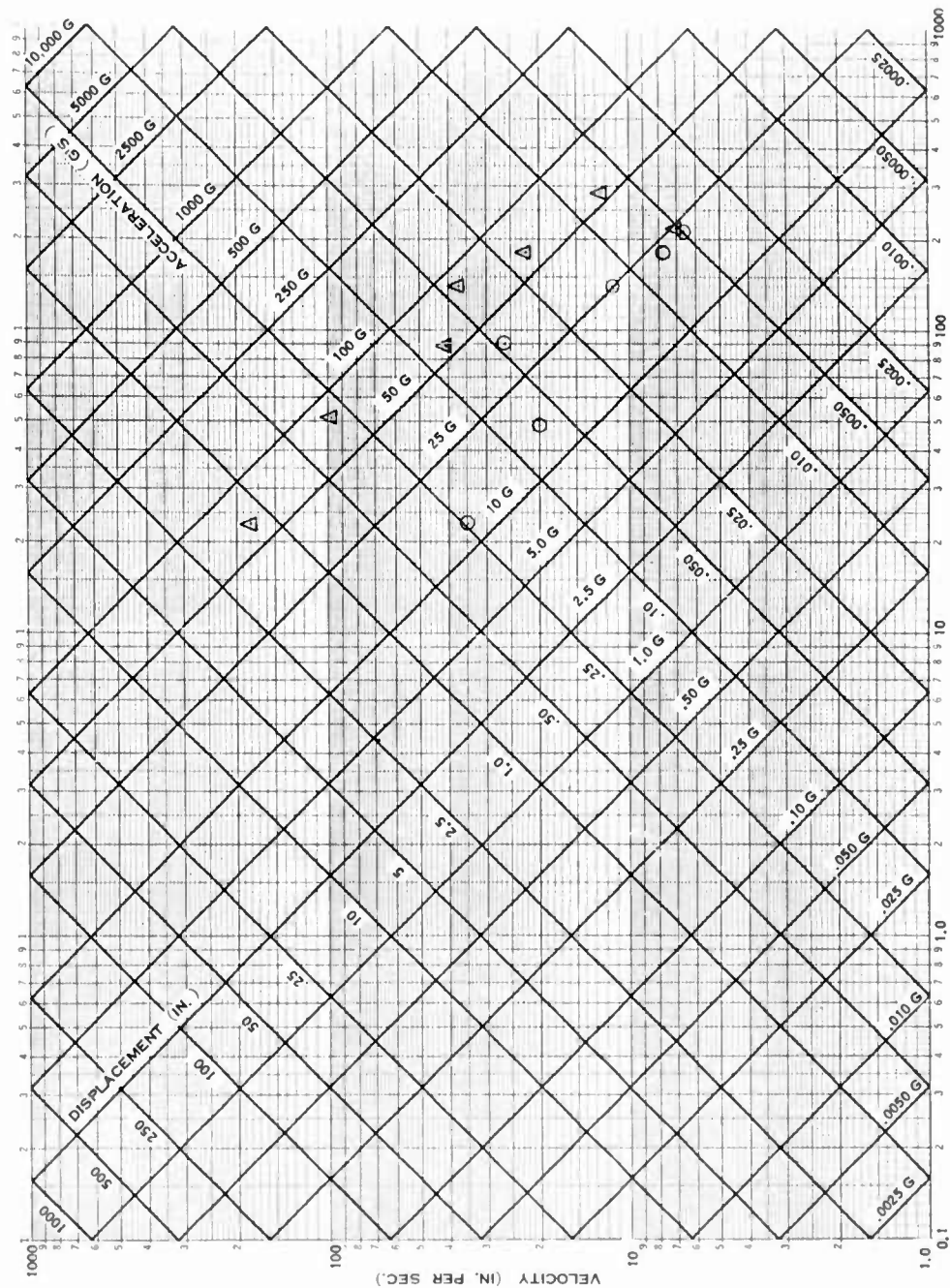


Figure 3 Vertical  $\Delta$  and horizontal  $\circ$  spectra at 185 feet, 10-foot depth of burial.

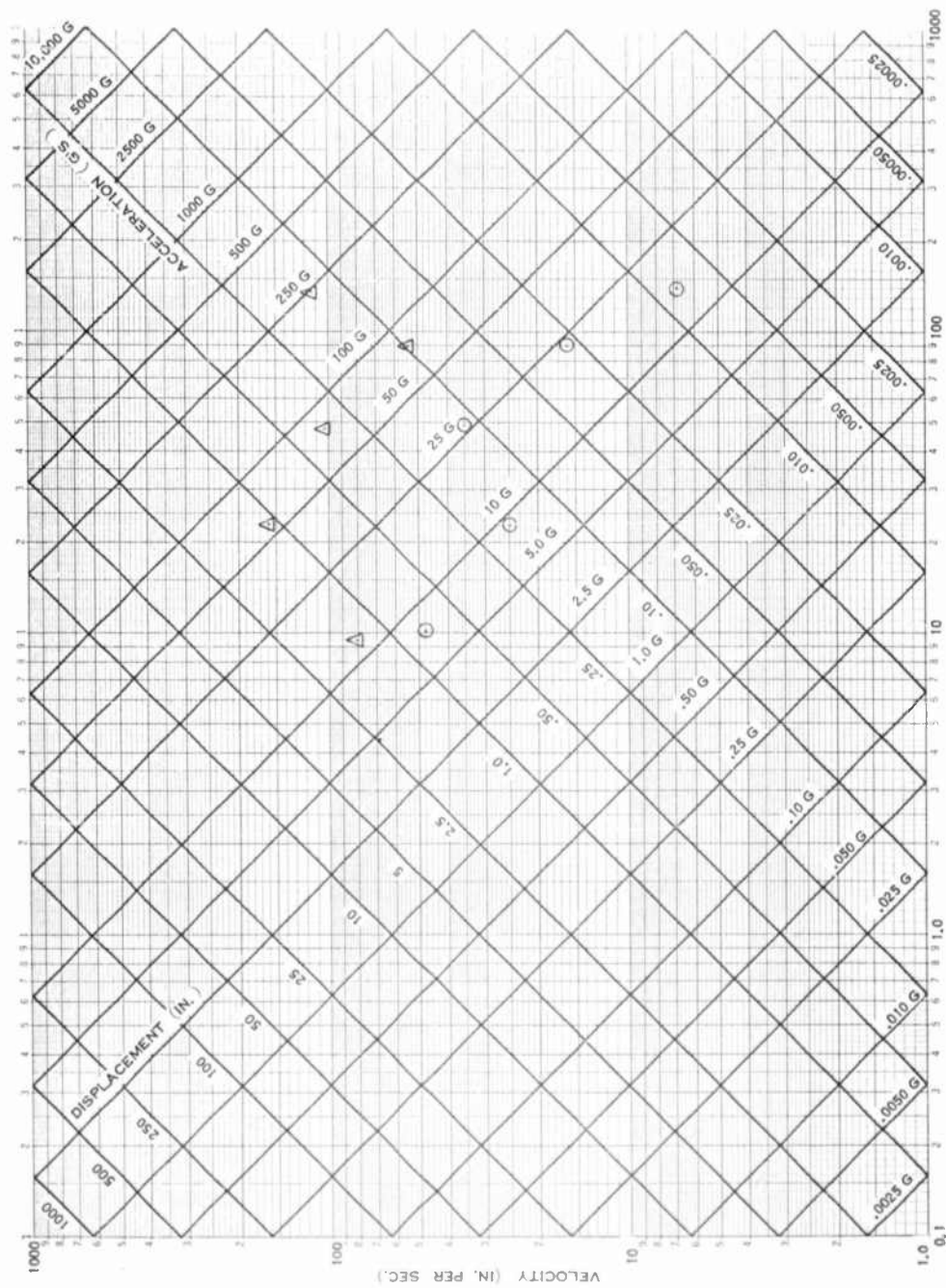


Figure 4 Vertical  $\Delta$  and horizontal  $\circ$  spectra at 200 feet, 10-foot depth of burial.

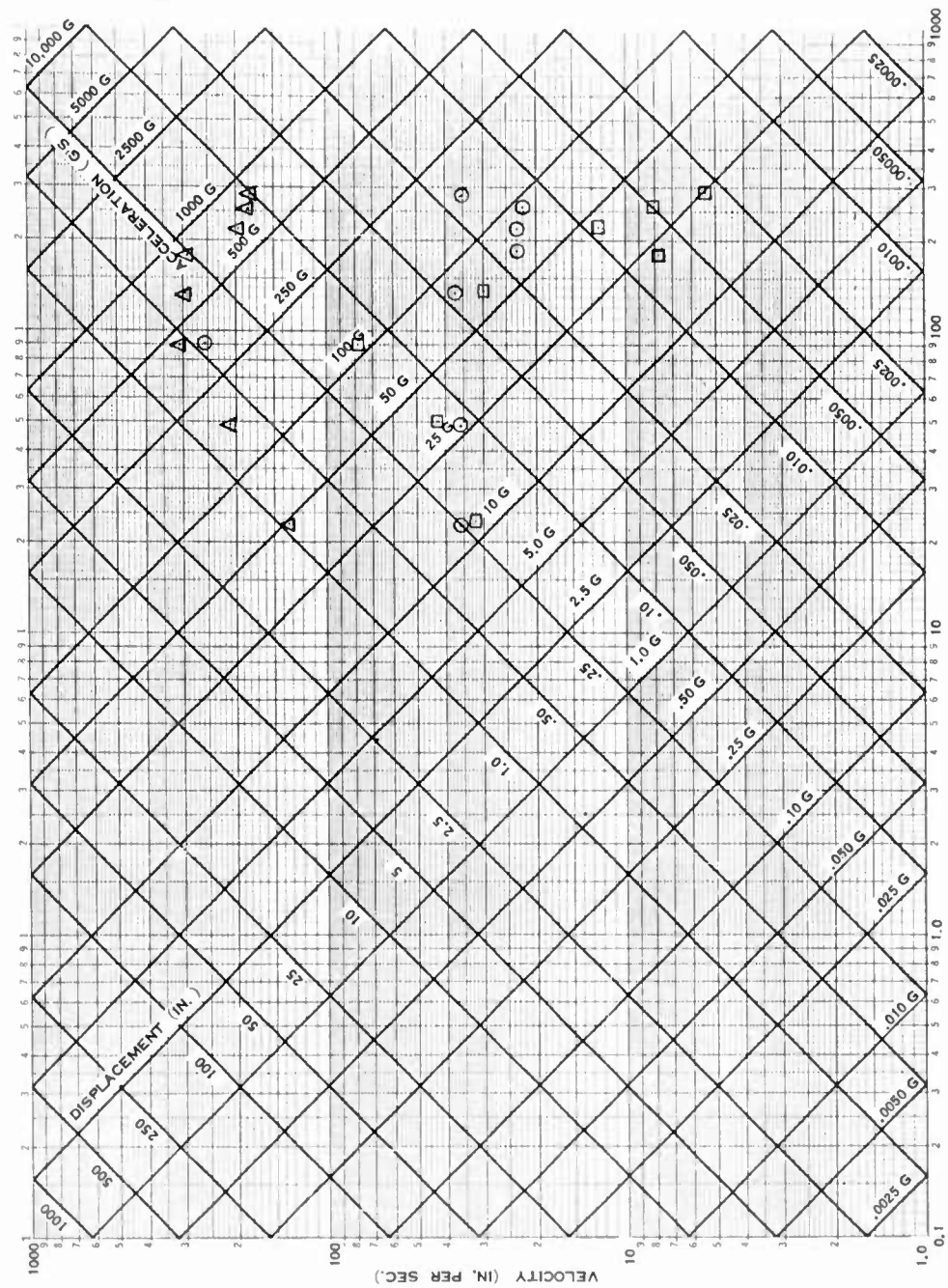


Figure 5 Vertical  $\Delta$ , horizontal  $\circ$  and tangential  $\square$  spectra at 200 feet, surface.



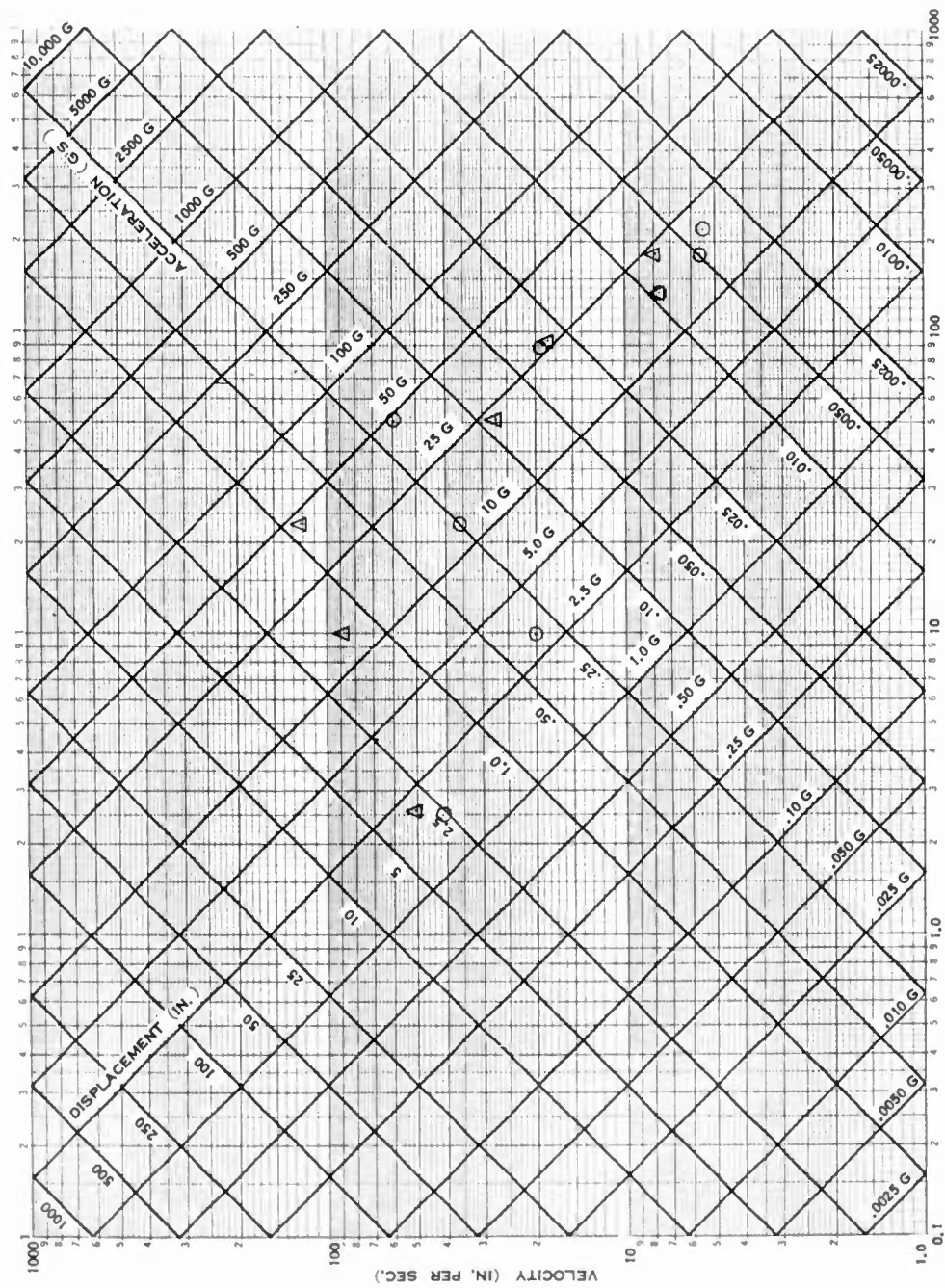


Figure 6 Vertical Δ and horizontal ○ spectra at 246 feet, 10-foot depth of burial.

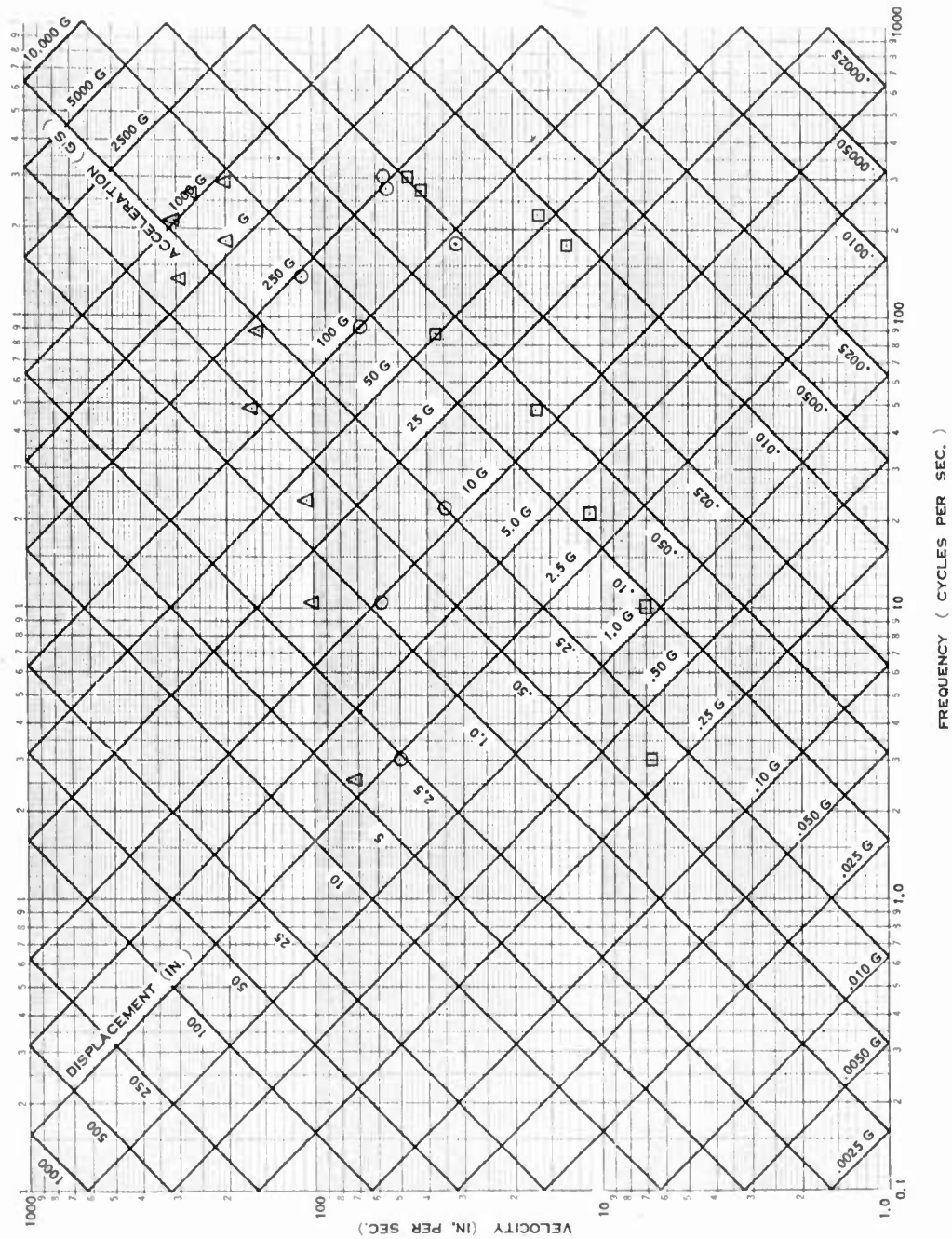


Figure 7 Vertical  $\Delta$ , horizontal  $\circ$  and tangential  $\square$  spectra at 246 feet, surface.

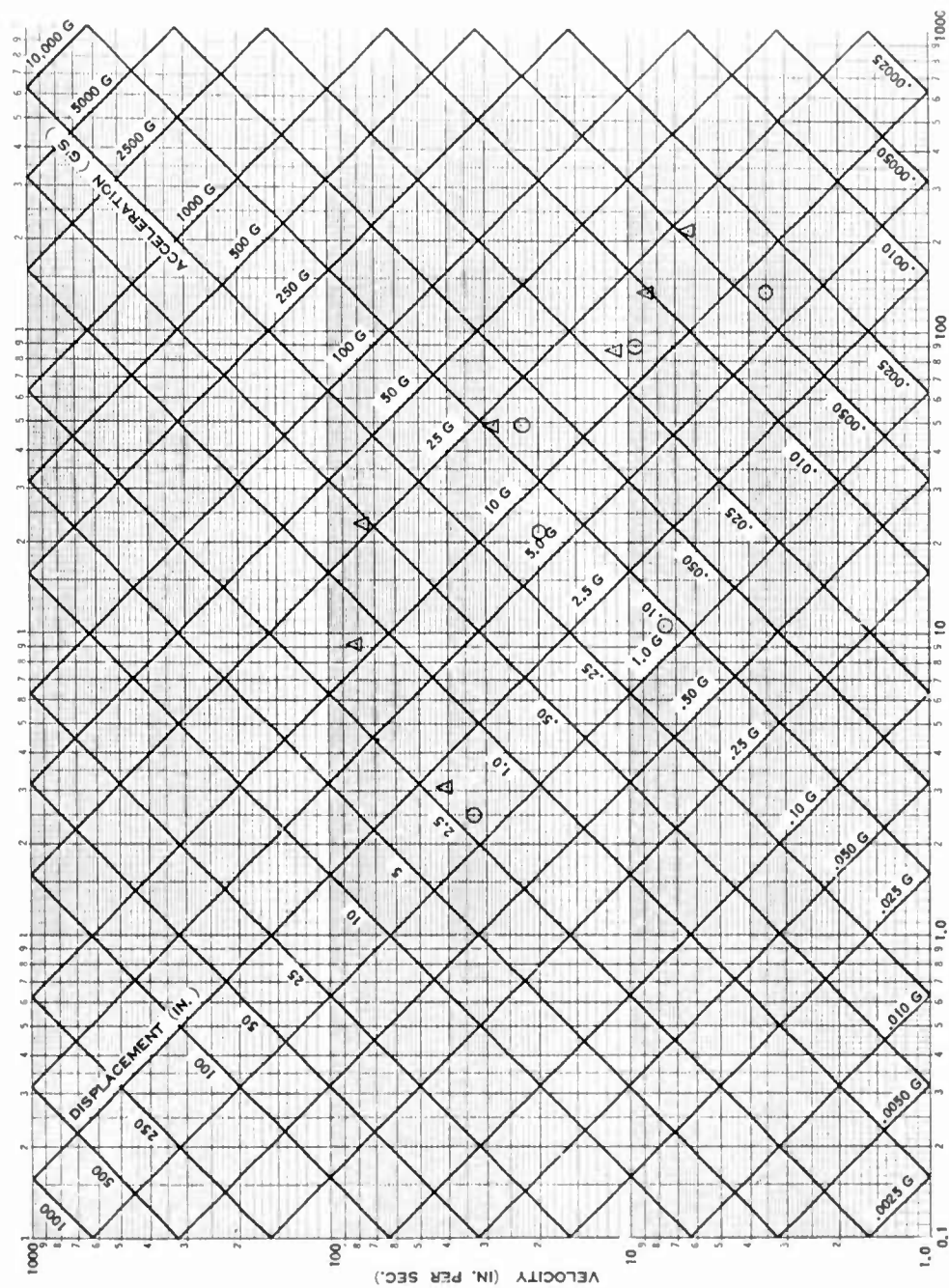


Figure 8 Vertical  $\Delta$  and horizontal  $\circ$  spectra at 290 feet, 10-foot depth of burial.

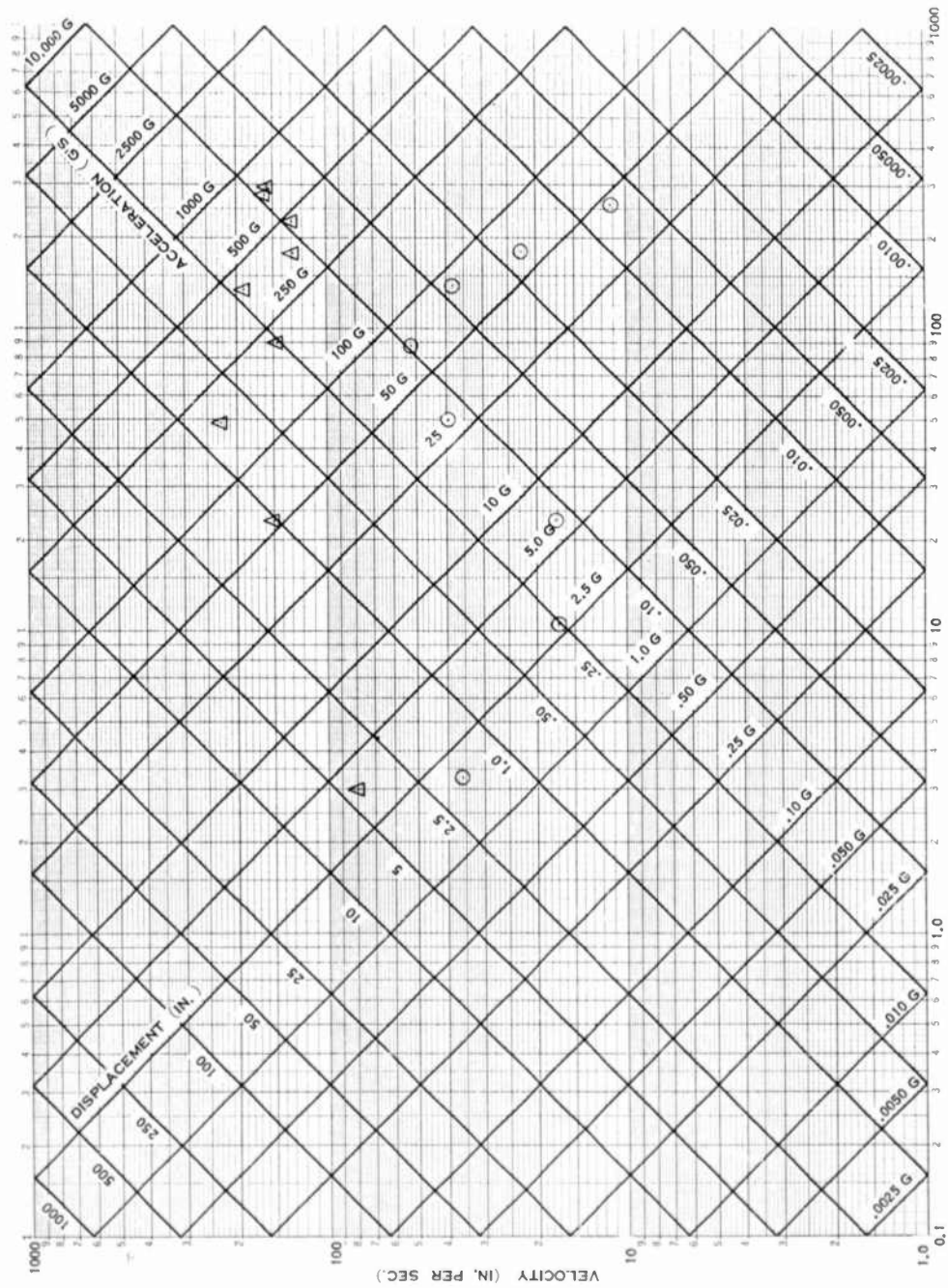


Figure 9 Vertical Δ and horizontal ○ spectra at 290 feet, surface.

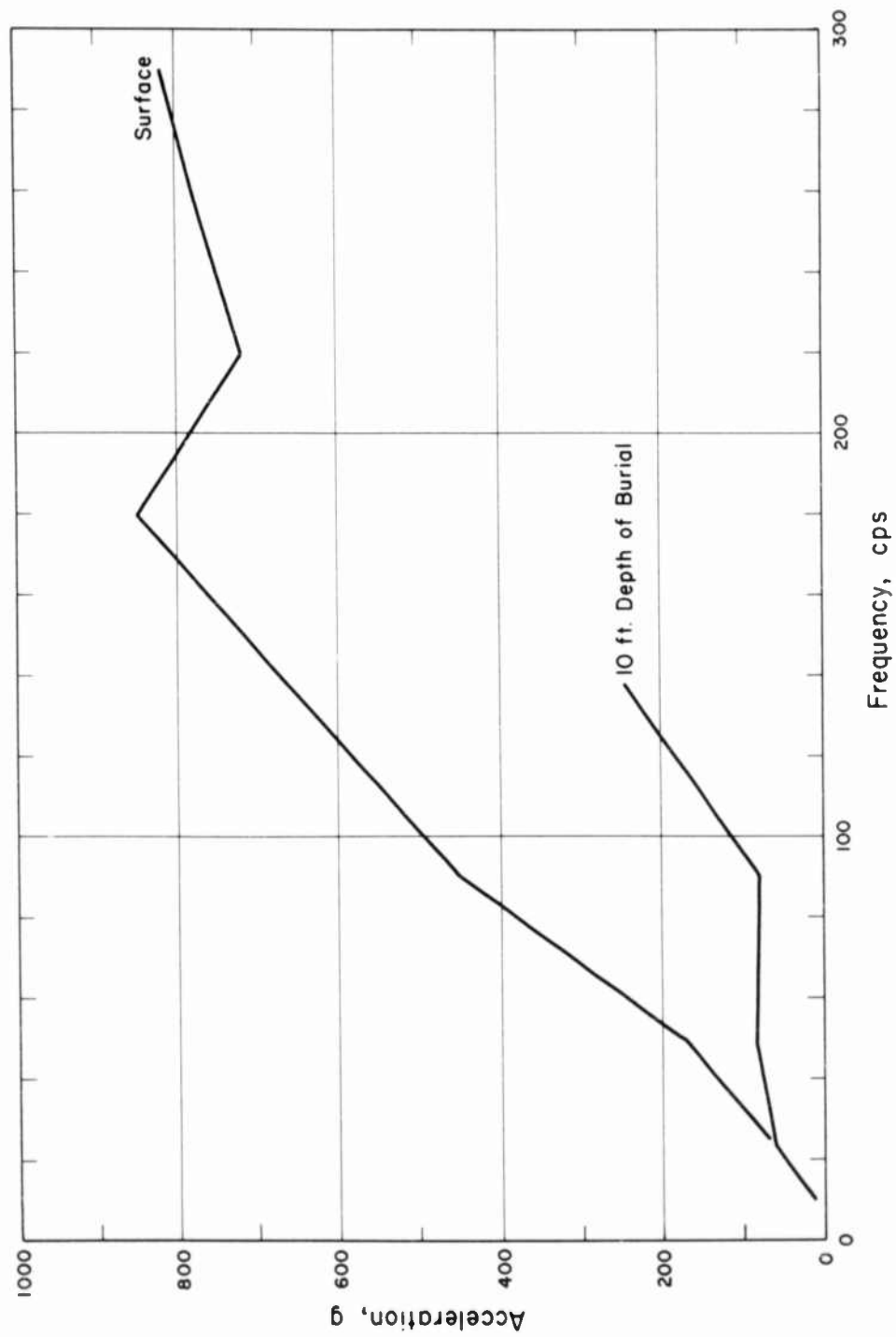


Figure 10 Vertical acceleration versus frequency at the surface and 10-foot depth, 200-foot range.

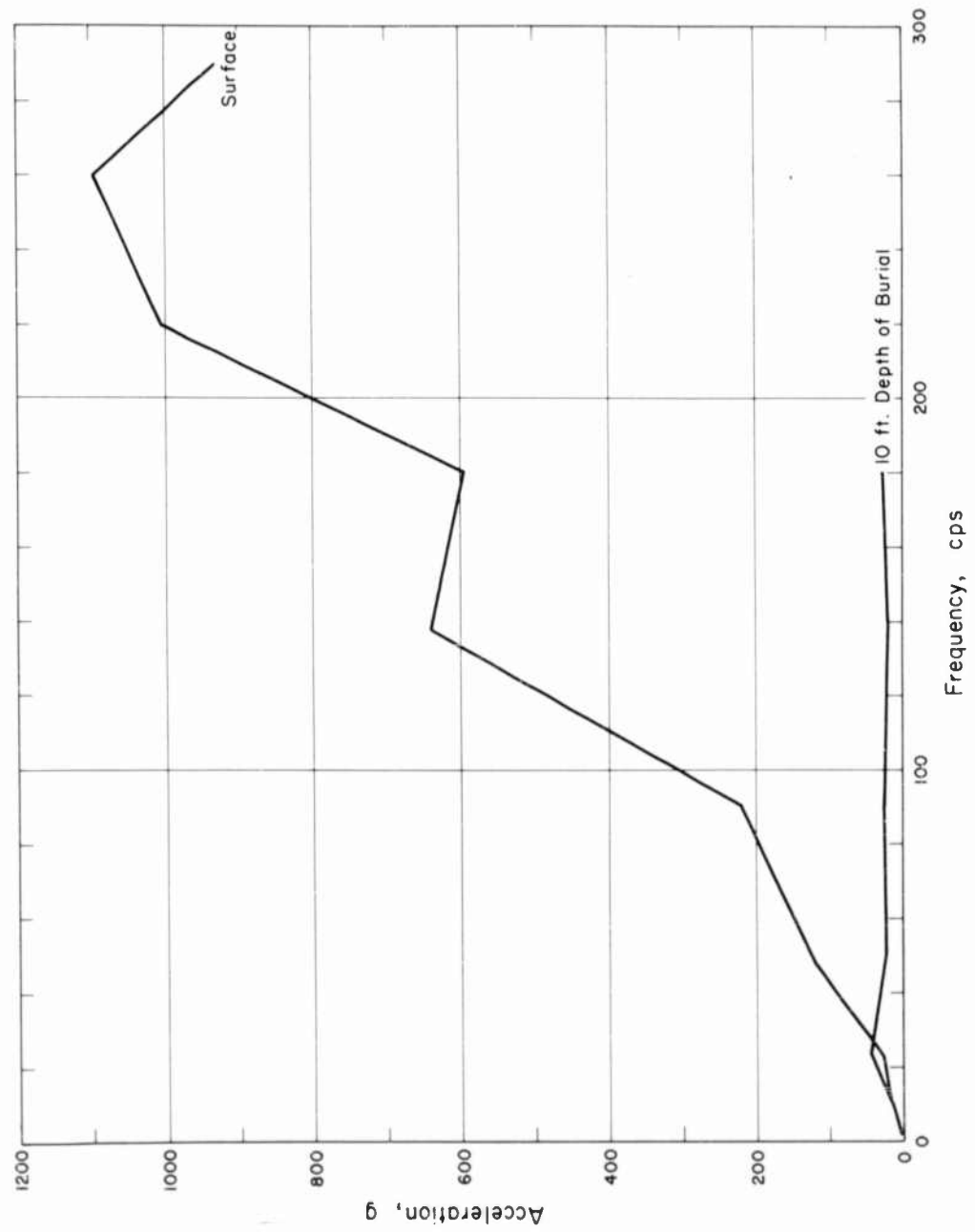


Figure 11 Vertical acceleration versus frequency at the surface and 10-foot depth, 246-foot range.

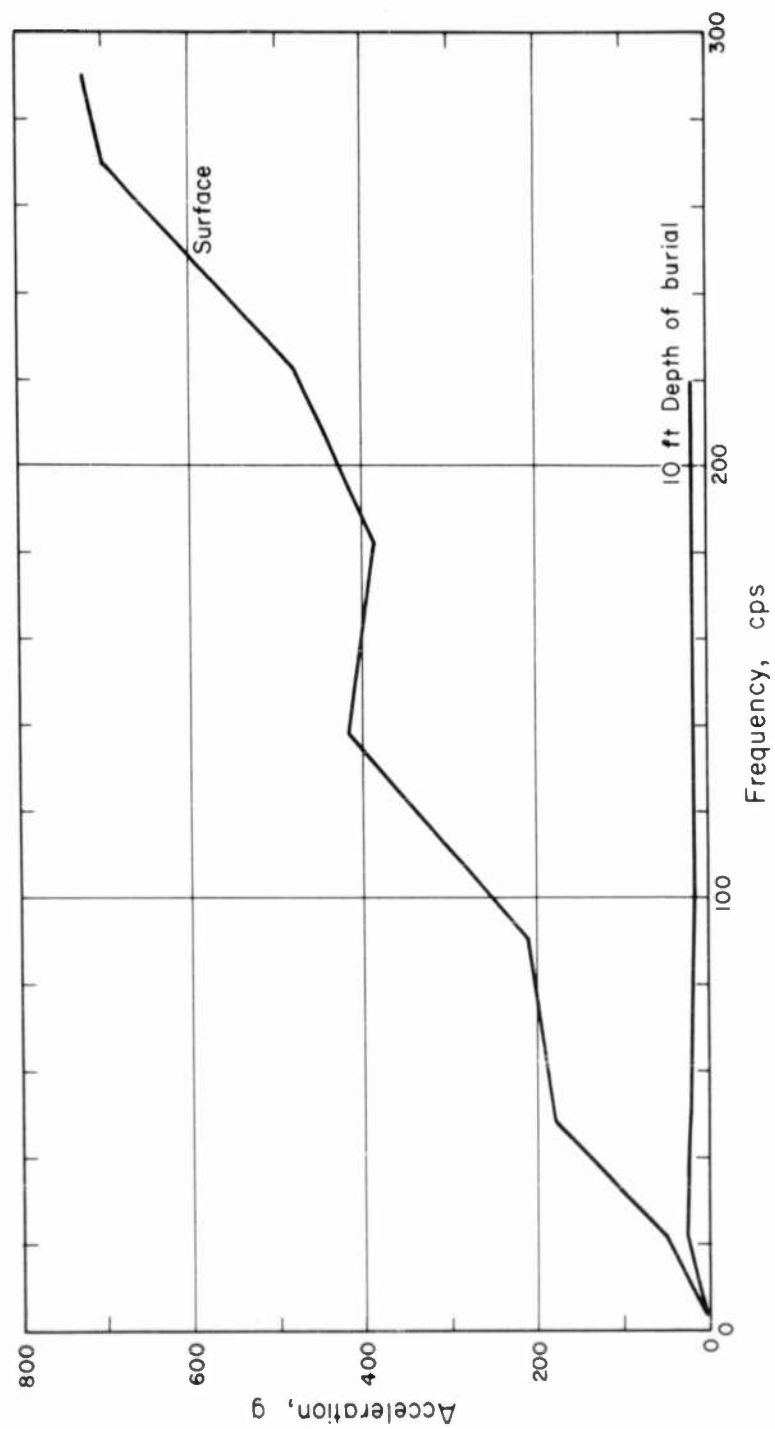


Figure 12 Vertical acceleration versus frequency at the surface and 10-foot depth, 290-foot range.

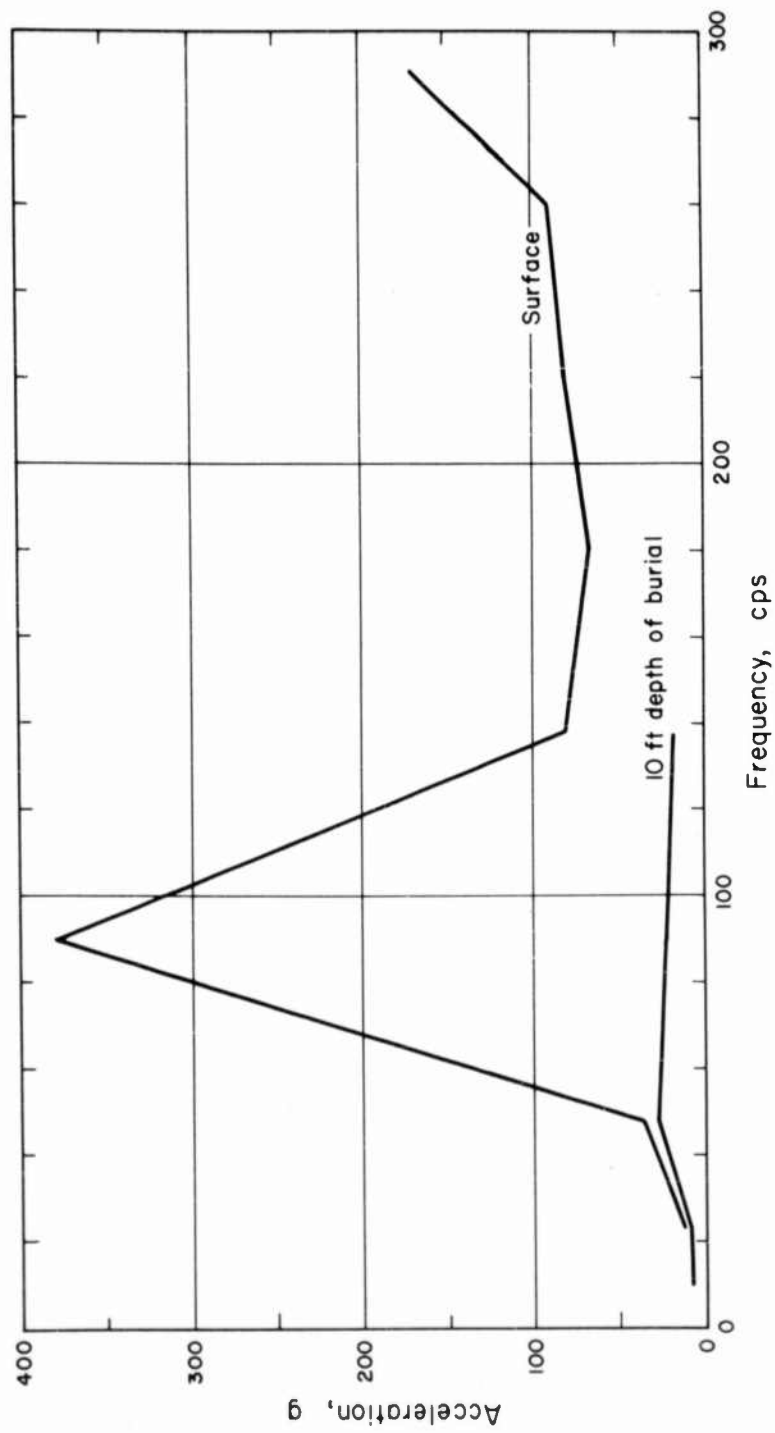


Figure 13 Horizontal acceleration versus frequency at the surface and 10-foot depth, 200-foot range.



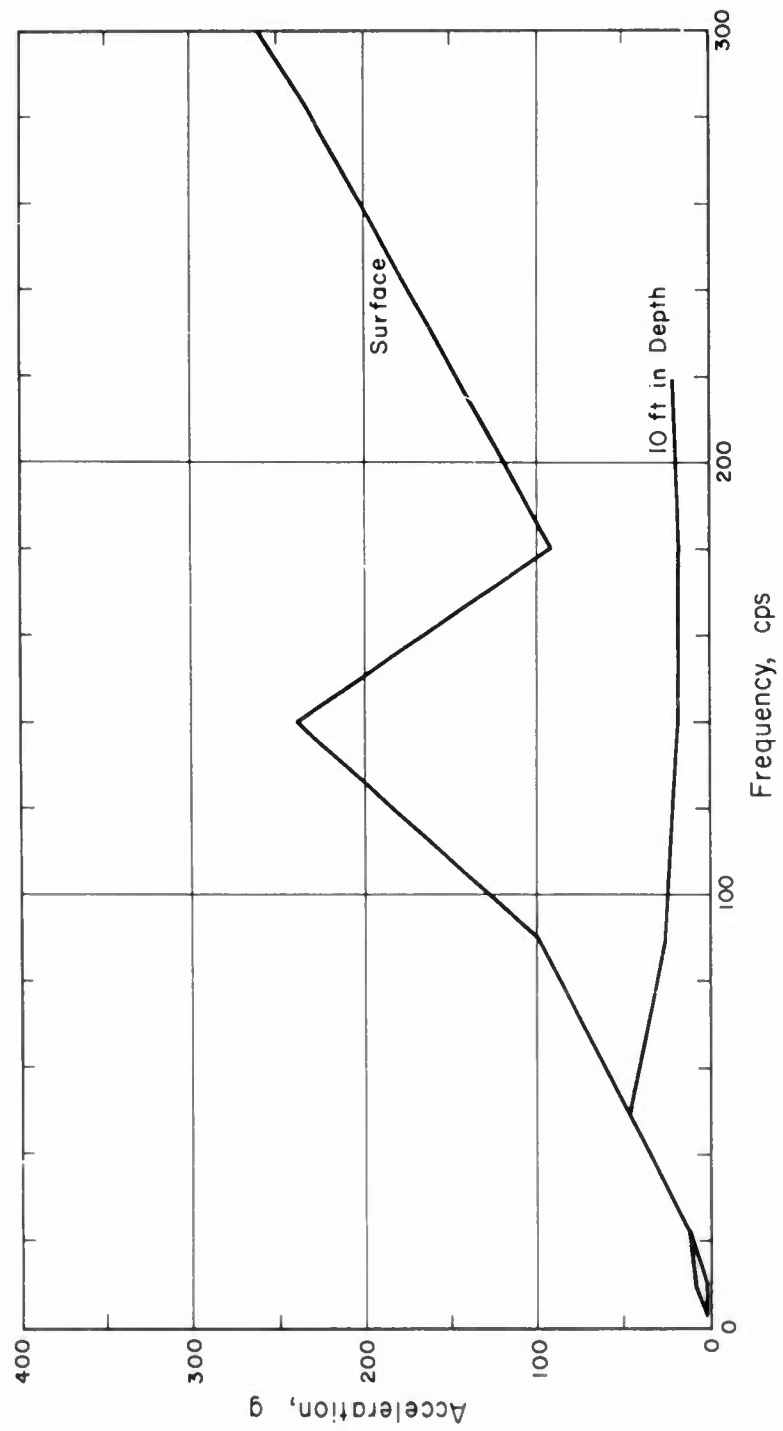


Figure 14 Horizontal acceleration versus frequency at the surface and 10-foot depth, 246-foot range.

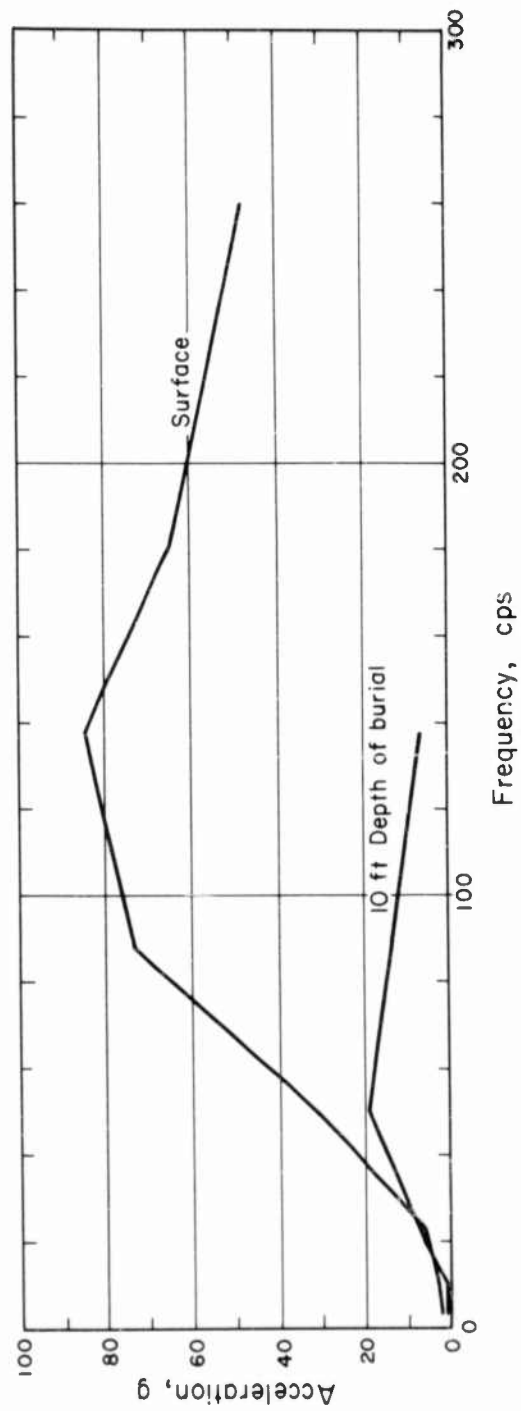


Figure 15 Horizontal acceleration versus frequency at the surface and 10-foot depth, 290-foot range.

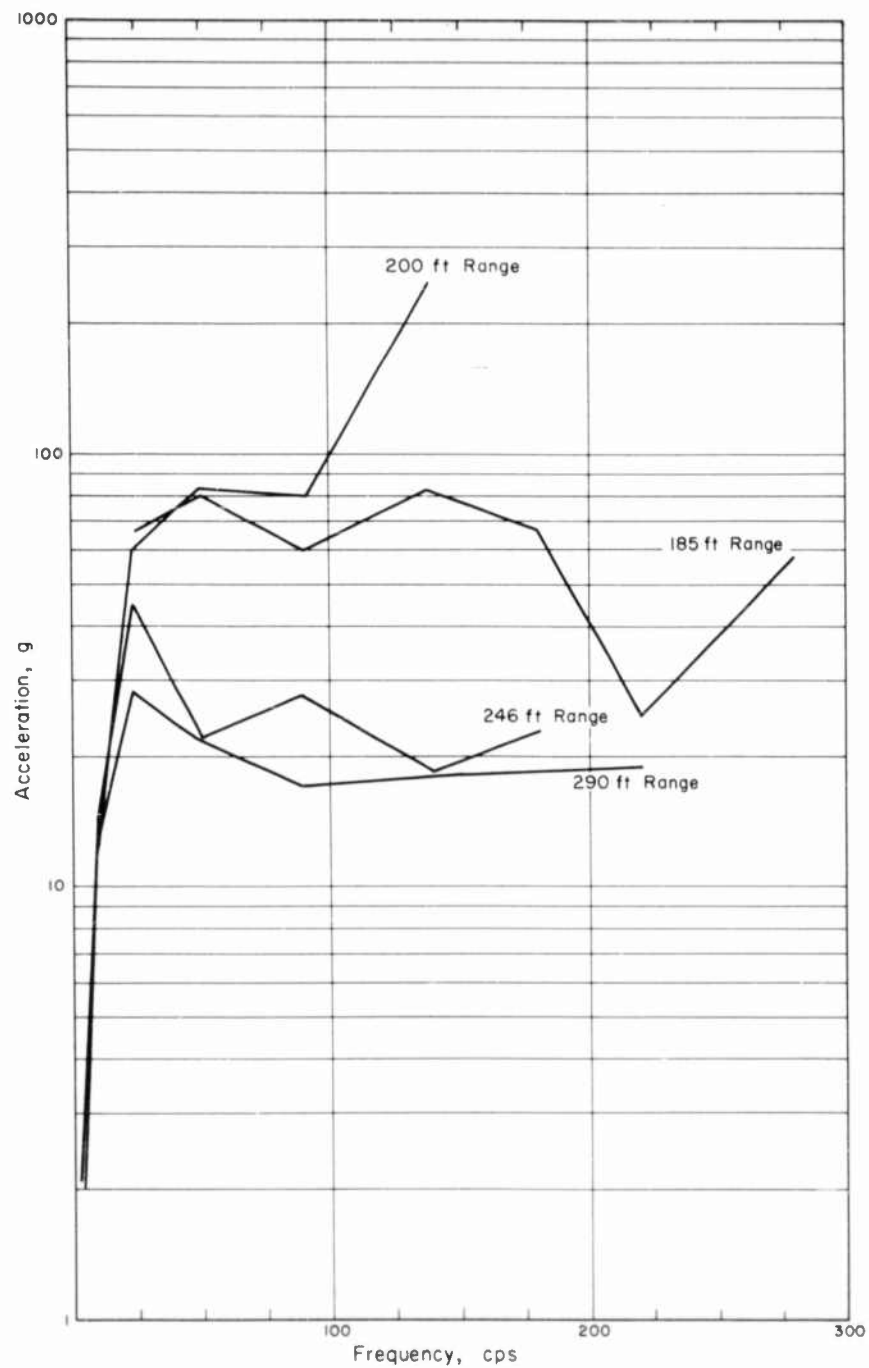


Figure 16 Vertical acceleration versus frequency at 10-foot depth for ranges of 185, 200, 246, and 290 feet.

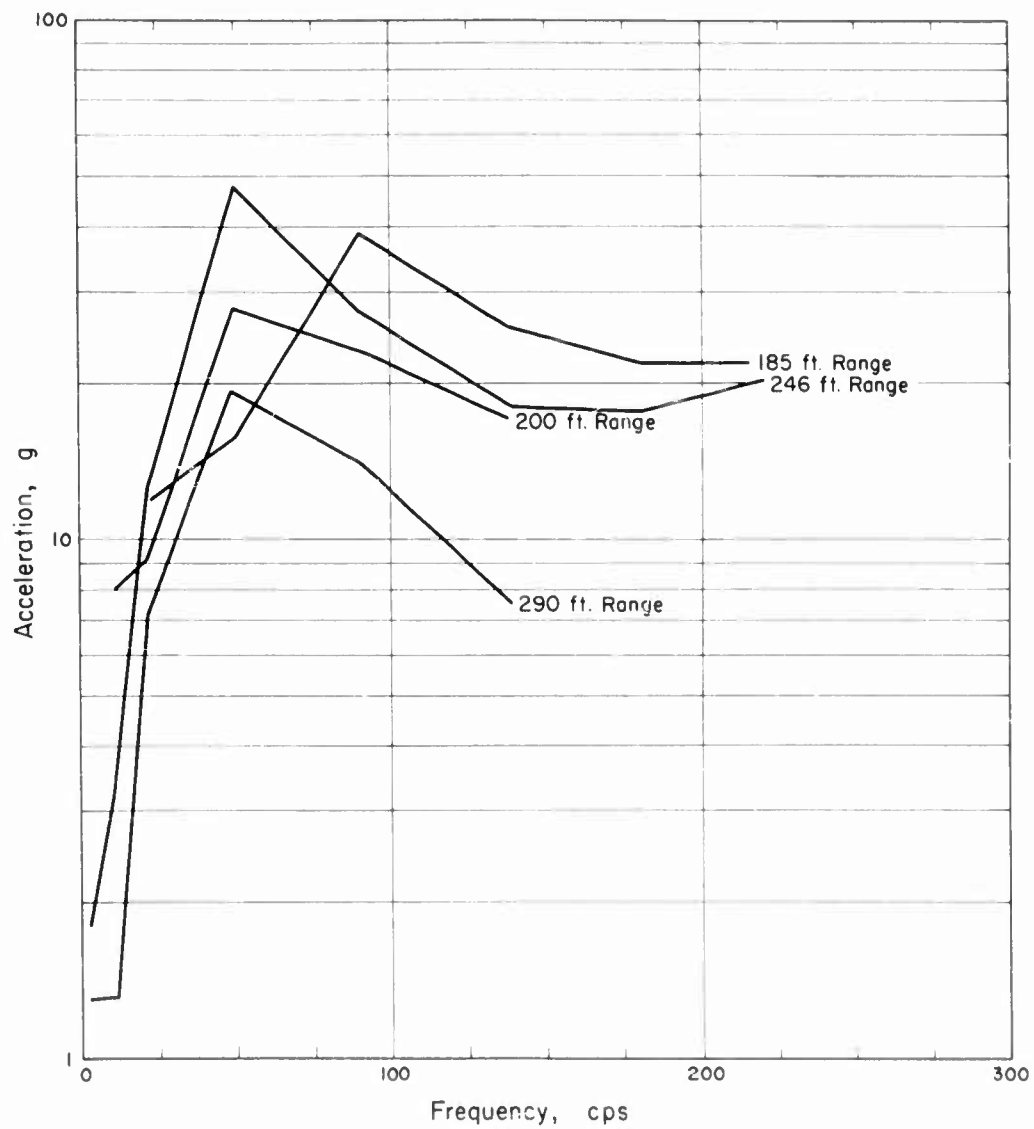


Figure 17 Horizontal acceleration versus frequency at 10-foot depth for ranges of 185, 200, 246, and 290 feet.

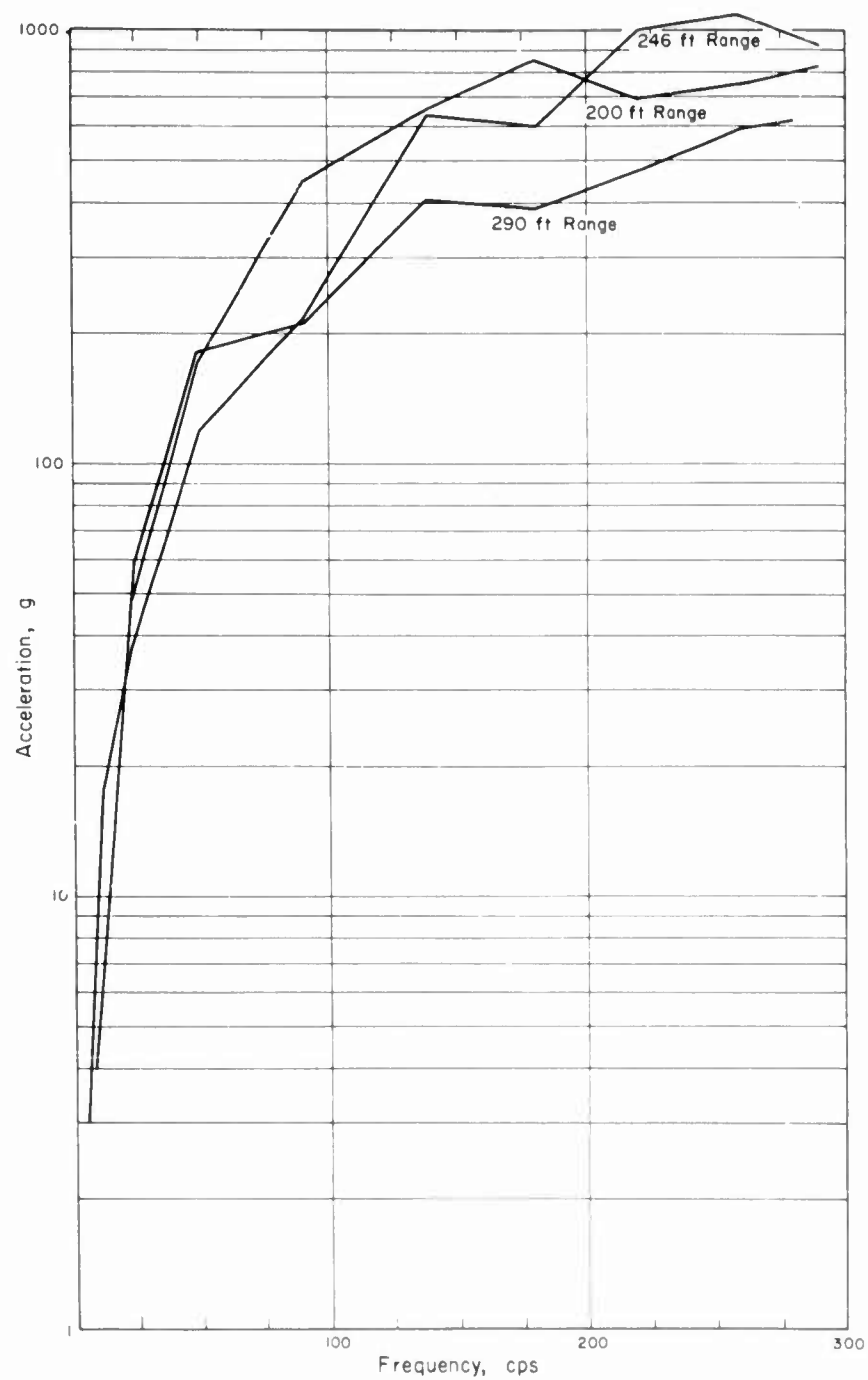


Figure 18 Vertical acceleration versus frequency at the surface for ranges of 200, 246, and 290 feet.

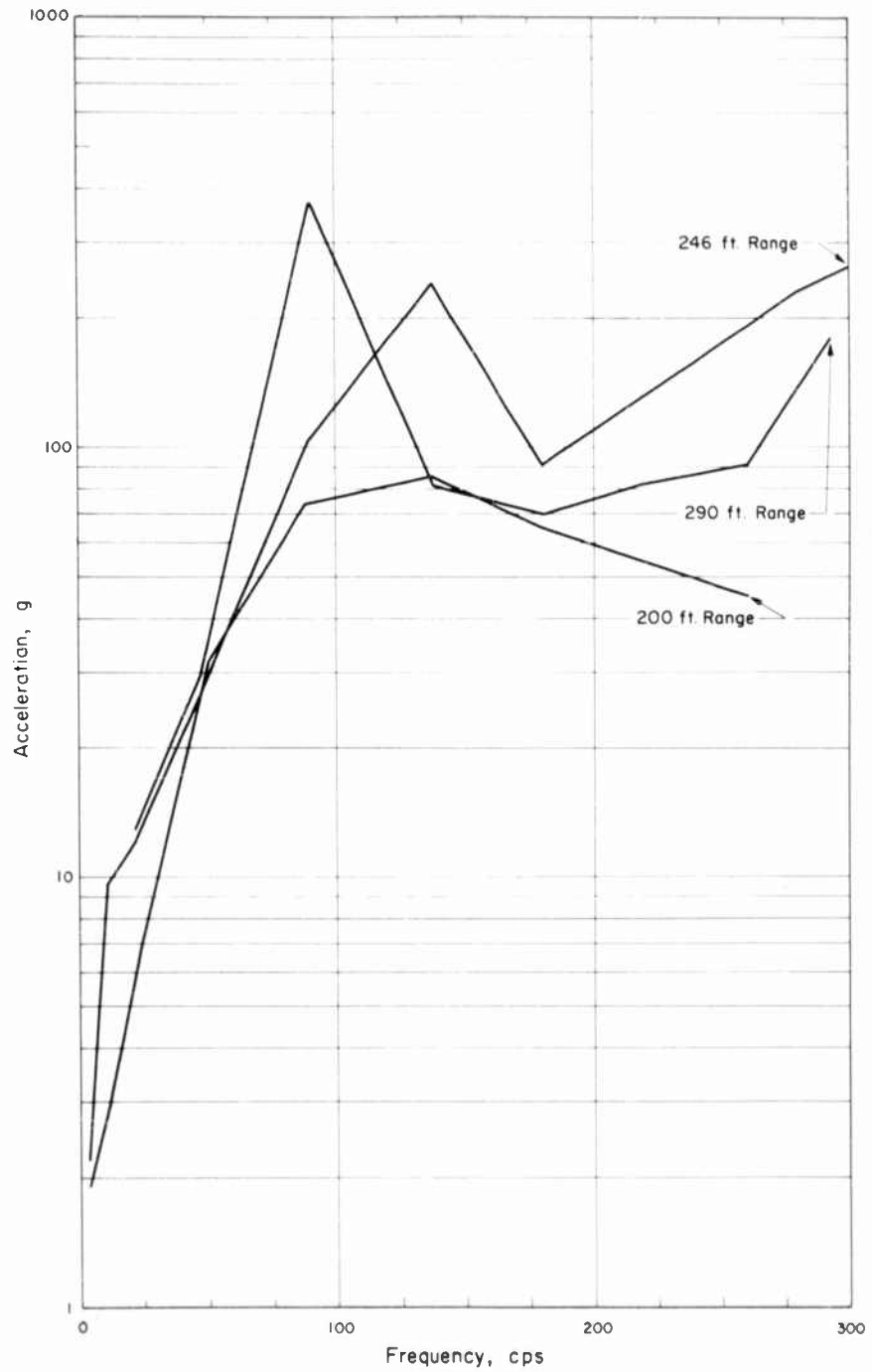


Figure 19 Horizontal acceleration versus frequency at the surface for ranges of 200, 246, and 290 feet.

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